DATA DISPLAY STUDY

Second Quarterly Report

1 March to 1 June 1963

Report Number 2

Contract No. DA-36-039 SC-90855
U.S. Army Signal Research and Development Laboratory
Fort Monmouth, New Jersey

NCR

THE NATIONAL CASH REGISTER COMPANY
ELECTRONICS DIVISION
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Hawthorne, California

DATA DISPLAY STUDY

QUARTERLY REPORT NO. 2
1 March to 1 June 1963
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by
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1. PURPOSE

The purpose of this program performed under Contract DA-36-039 SC-90855 is to conduct a research study and an experimental investigation to determine techniques, methods of application and design criteria for automatically converting digital data into display form including graphs, maps, and pictorial displays.

2. ABSTRACT

During the second period of this contract, effort has been directed toward completing theoretical evaluation of the Counter-Rotating Optical Wedge (CROW) system and in continuation of the design of the Electronic PhotochromIC (EPIC) system. Analyses are included on the phosphor, projection, and system considerations of this EPIC display technique.

3. REPORTS AND CONFERENCES

a. Monthly Report for period of 1 March 1963 to 31 March 1963 by H. L. Bjelland.

b. Monthly Report for period of 1 April 1963 to 30 April 1963.

c. Contractor visit on 3 April 1963 of H. Bjelland and W. Leisner of NCR at Vacuum Tube Products Division of Hughes Aircraft at Oceanside, California, to discuss the feasibility of utilizing the Tonotron type of tube writing on photochromic material. A technical discussion of this visit is included under Paragraph 4. Factual Data.

d. Contractor visit on 9 April 1963 to General Dynamics, San Diego, California with H. Bjelland, W. Leisner, and S. Mak of NCR and Jim Redman of General Dynamics. The purpose of this visit was to conduct experiments with the fiber optic Charactron writing on photochromics. Refer to Paragraph 4. Factual Data.

e. Contractor visit on 18 April 1963 to Litton Tube Division, San Carlos, California by H. Bjelland and S. Mak of NCR, and David Kline of Litton to conduct tests on the Litton fiber optic high-resolution cathode ray tube writing on photochromic material.

f. Visit by H. Bjelland of NCR, Hawthorne, California, with Dr. Maclin Hall of NCR, Dayton, Ohio on 6 May to discuss basic phosphor work which is being accomplished by NCR Dayton. Details of this discussion are presented in Paragraph 4, Factual Data.

g. Visit made by H. Bjelland of NCR on 8 May 1963 with E. Kral, W. Huber and F. J. Petschauer of Fort Monmouth, New Jersey. The purpose of this visit was to review the First Quarterly Progress Report and to discuss progress accomplished to date.

4. FACTUAL DATA

During the past quarter, effort has been directed toward the continued theoretical evaluation of the Counter-Rotating Optical Wedge (CROW) System and in further detailed analysis and design of the Electronic PhotochromIC (EPIC) Display System. An analysis and summary of the work accomplished to date on the CROW System is included in Paragraph 4.1. The effort accomplished on the EPIC System is discussed in Paragraph 4.2.

4.1 CROW DISPLAY SYSTEM. The present electromechanical system being utilized in the photochromic display technique requires an X-Y mechanism to position the writing beam in X and Y axes. This technique was described in the First Quarterly Report. Considerable progress has been made in increasing the optical writing speeds of the photochromic display. Some progress has been made in increasing the slewing speed of existing electromechanical devices. To fully utilize the improved optical writing speed capabilities of the electromechanical display system, new electromechanical techniques of writing were considered. After examining a number of possible techniques, the CROW System seemed to provide the most promise of being able to retain the optical speed and provide a considerably increased electromechanical speed. Therefore, investigation was conducted in the first quarter and through a portion of the second quarter of this contract to further investigate this technique as a parallel effort with the EPIC system. The effort was conducted from initial analysis through preliminary design until analytical feasibility of the technique was established. A summary of the analytical work and preliminary design is included in the following paragraphs.

4.1.1 Analysis and Preliminary Design of CROW System. A summary of the analysis performed on the CROW system is provided in the following paragraphs. To derive the diameter of the effective exit pupil D of the wedge system, refer to Figure 1.

$$\mathrm{Tan}\,\theta = \frac{y}{f}$$

$$\text{and } \ell = d\,\mathrm{Tan}\,\theta$$

$$= d\,\frac{y}{f}$$

where y = y-axis deflection

f = lens focal length

d = wedge-to-writing lens distance

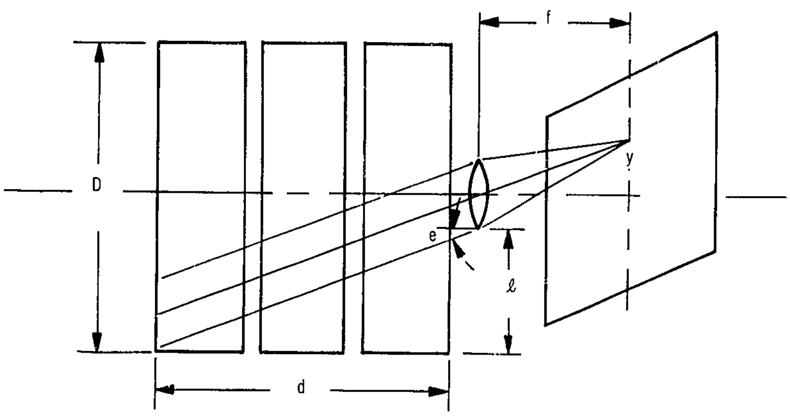

Figure 1. Derivation of CROW System Optics

From Figure 1

$$D = 2\ell + \text{lens diameter}$$

since

$$\text{Lens diameter} = \frac{f}{F\#}$$

$$D = 2\ell + \frac{f}{F\#}$$

where $F\# =$ lens effective f number

substituting

$$\ell = \frac{dy}{f}$$

$$D = 2\frac{dy}{f} + \frac{f}{F\#}$$

or

$$0 = f^2 - \frac{F\#D}{2} f + 2dyF^{\#}$$

and by solving for f, the following is obtained

$$f = \frac{F\#D}{2} \pm \frac{F\# \sqrt{D^2 \frac{-8dy}{F\#}}}{2}$$

It is to be noted that f must have positive real values greater than zero. If the values of D, d, and y are held constant, then the smallest value that the F# can have is determined from

$$\sqrt{D^2 \frac{-8dy}{F\#}} = 0$$

$$\therefore F\# = \frac{8dy}{D^2}$$

the corresponding value of f is

$$f = \frac{F\#D}{2}$$

In brief, the fastest optical system will have a

$$F\# = \frac{8dy}{D^2}$$

and a focal length

$$f = \frac{F\#D}{2}$$

To analyze a typical example, let the photochromic area be 2 inches square. Each wedge pair, including the mechanical mounting, should not exceed a thickness of 1.5 inches. The maximum permissible diameter of the wedges is 2.5 inches. This means that:

$$y = \sqrt{\frac{2^2 + 2^2}{2}}$$

$$= \sqrt{\frac{8}{2}}$$

$$= 1.414 \text{ inches}$$

$$d = 1.5 + 1.5 + 1.5$$

$$= 4.5 \text{ inches}$$

$$D = 2.5 \text{ inches}$$

$$F\# = \frac{8(4.5)\ (1.4)}{(2.5)^2}$$

$$F\# = 8.06$$

The focal length is

$$f = \frac{F\#D}{2}$$

$$= \frac{(8.06)\ (2.5)}{2}$$

$$f = 10.01 \text{ inches}$$

The required writing lens diameter will be

$$\frac{f}{F\#} = \frac{10.01}{8.06}$$

$$= 1.25 \text{ inches}$$

and the lens half angle is

$$\text{Tan}\ \theta = \frac{1.414}{10.01}$$

$$\theta = 8.5^0$$

4.1.2 Summary of Progress with CROW System. Effort on the CROW System has been extended to the point where preliminary feasibility has been established. The next logical step would be to proceed with a detailed design of the lenses, wedges, and overall optical system, and to build and test this technique. Also, to date, very little consideration has been given to the other system problems, such as:

a. Mechanical design

b. Feedback voltage technique

c. Accuracies and speeds attainable

Although the CROW technique appears to offer significant improvement over the present electromechanical system, de-emphasis of the investigation of this technique is planned at this time to permit concentration on the EPIC System. This conclusion is based upon the greater potential and excellent progress achieved to date on the EPIC System and upon the practical limitations of funds and time.

4.2 EPIC DISPLAY SYSTEM. The EPIC Display technique promises a considerable number of advances in the state-of-the-art of the photochromic display technology. First, the system is non-mechanical, providing increased reliability and simplicity. In addition, the system offers a multitude of advantages inherent in a CRT type of display system, e.g., rapid plotting of random and sequential data. Also, considerable developments used in direct view CRT displays, such as character generators and militarized circuits, will be applicable to the EPIC display.

Prior to the Data Display Study, NCR had engaged in the development of CRT photochromic writing using conventional optics. However, since no special lenses were designed, the efficiency was poor and speeds were prohibitively slow. The advent of the fiber-optic CRT immediately provided a possible improvement of about 50 times over conventional CRT optical systems. A writing capability approaching a useful speed is then provided.

The operating parameters and related writing speeds postulated for the EPIC display are best understood by a study of the theoretical formulae and corresponding experimentation. Consequently the following discussion of the EPIC Display System includes a delineation of test results obtained through experimentation with selected manufactured devices.

The first experimental efforts were conducted at the facilities of various manufacturers with CRT devices developed for similar applications. In some instances, the CRT was not actuated in an optimum manner for the purposes of this study. However, the access to these facilities was of positive value to the study program. A fiber-optic Charactron CRT previously developed by General Dynamics Electronics (GDE) was set up for our

tests. GDE made available a Charactron CRT with a fiber-optic face plate containing three types of phosphors: P15, P16, and P22. The face plate was composed of 3 to 5 micron fibers and was 1/4-inch thick. Character on-time was set at 100 microseconds and the CRT was programmed for a 40 character message. A drum memory was used to recircluate this message to the CRT. Dead time was 20 milliseconds in each cycle and 150 microseconds from character to character, resulting in an effective character repetition rate of about 30 per second. The beam current was 10 microamperes and the accelerating voltage was 24 kv. A character size of 0.03-inch was used. Preliminary experiments ascertained that the P16 phosphor was definitely the most suitable for writing on photochromics. With P16 phosphor and the system parameters enumerated in the preceding statements a 20-second exposure was required for the 40 characters. These Charactron characteristics are summarized in Table 1.

TABLE 1. CHARACTRON

CHARACTERISTIC	SPECIFICATION
Ultor Voltage	24 kv
Beam Current	10 μ amp
Phosphor	P15, P16, P22
Faceplate	3 to 5 micron fibers; 1/4-inch thick
Character On-time	100 μsecs
Character Size	0.03 inch

In the initial series of tests, GDE was concerned about overdriving the tube; however, NCR suggested that the repetition rate and screen intensity be increased for a second series of tests. With the second series, the message was repeated 85 times per second. A photochromic plate was exposed to a good contrast in 10 seconds, an acceptable contrast in 5 seconds, and a poor contrast in 2 seconds. No method of measuring optical density was available, and therefore, only an estimate of contrast was made.

The Tube Division of Litton Industries located in San Carlos, California has also accomplished developments for the Military utilizing a high-resolution fiber-optic CRT to write data on Kalvar film. Since the Kalvar film has essentially the same sensitivity in both magnitude and light spectrum as photochromics, it was thought these tests would be of value.

A console containing the necessary equipment to scan a 35 mm slide and to apply this data to a high-resolution fiber-optic CRT was operated by Litton. The Litton fiber-optic CRT specifications are listed in Table 2.

TABLE 2. LITTON FIBER OPTIC CRT

CHARACTERISTIC	SPECIFICATION
Tube Type	E2A16B
Anode Voltage	40 kv
Anode Current	varied with duty cycle
Deflection	magnetic
Resolution	1000 line
Tube Length	less than 18 inches
Tube Face	2-inch by 2-inch
Fiber-Optic Active Areas	1-5/8 by 1-5/8 inches

Tests were conducted with different types of projected data, varying from a resolution chart to photographs. Litton representatives had previously estimated that an entire raster could be written on Kalvar film in less than one second using the Litton CRT under maximum light output conditions. For the NCR Tests, the average beam current was set at approximately 50 to 100 microamperes. Approximately 6 to 8 seconds were required to write the entire raster with adequate contrast. The character repeatability was less than desired and some blurring occurred. Thus, the writing time was increased to compensate for distribution of the light energy over a larger area.

The Litton fiber-optic CRT operates with the anode at ground potential. Since a voltage differential of about 40 kv exists between anode and cathode, this necessitated unconventional CRT circuits; for example, the video amplifier is isolated for 40 kv and video signals are transmitted by rf between chassis.

A theoretical analysis of the photochromic writing speed is presented in Paragraph 4.2.1. This analysis is compared with the writing speeds achieved in experiments with both the General Dynamics Electronics and Litton CRT devices.

From the measurements in Paragraph 4.2.1, it was ascertained that the present CRT light output of the EPIC system would not permit the exposure of the photochromics in

a single sweep of a CRT. To make the information available for 10 to 100 pulse sweeps, some type of memory device is necessary. Because a short memory external to the display is required, consideration was then given to writing directly on photochromics and using the long storage capabilities of the Tonotron tube to be integrated by the photochromic material. To investigate this approach, a visit was made to the Vacuum Tube Products Division of Hughes Aircraft Company at Oceanside, California, to discuss the Hughes Tonotron Memory tube. Discussion with Hughes technical personnel produced the data listed in Table 3.

TABLE 3. HUGHES TONOTRON MEMORY TUBE

CHARACTERISTIC	SPECIFICATION
Resolution	50 to 70 lines per inch (may be increased by special design, but not likely to easily reach 1000 lines/in.)
Writing Speed	1 to 5 microseconds per spot (as low as 0.2 microseconds under special operation)
Persistence	Typically 1 to 5 minutes (up to 30 minutes with special techniques)
Erase Time	20 to 200 microseconds to erase entire screen

Initial calculations were made to estimate the photochromic CRT writing speed, using the following assumptions.

Anode Voltage	10 kv
Current	400 microamperes
Screen Size	3 inch diameter circular
Phosphor Efficiency	5 per cent

Power density of phosphor due to flood gun current covering entire screen is

$$\text{Power} = 10 \text{ kv} \times 400\ \mu\text{A}$$

$$= 4 \text{ watts}$$

$$\text{Area} = \frac{\pi (3)^2}{4}$$

$$= 7 \text{ in.}^2$$

$$\text{Power density} = \frac{4}{7}$$

$$= 0.57 \text{ watts/in}^2$$

With a phosphor having a 5 per cent efficiency and for simplicity assuming a 100 per cent efficient optical collection of available light energy, the light output is

$$0.05 \times 0.57 = 0.0285 \text{ watts}$$

The sensitivity of the photochromics is 2.15 watt-seconds per square inch. Assuming that the fibers are 100 per cent efficient, the entire screen will be written in

$$\frac{2.15}{0.0285} = 75 \text{ seconds}$$

The 75 seconds required to write the entire screen is too long a period to be useful. The writing speed will be further decreased because the efficiency of the optical system was not considered. This 75-second delay is required for writing one character or for rewriting the entire screen. However, the symbols become visible at a reduced density in a much shorter time, i.e., possibly 10 to 15 seconds, but require a full 75 seconds to reach full density. Therefore, because of the low resolution and slow writing time, no further work is being considered using the Hughes Tonotron.

Another major consideration in the EPIC System is the maximum obtainable phosphor temperature before burning and permanent damage occurs to the phosphor. The maximum temperature or T_{max} for typical phosphors is 300°C. This temperature is related to the energy applied to the phosphor through the following relation

$$I_D V \tau = T_{max} MC$$

where T_{max} = 300°C

M = Mass (typically 0.05 grams for phosphors)

C = Specific heat (0.2 calories/gm/°C)

T_{max} = Maximum phosphor temperature before burn

I_D = Beam current density

V = Ultor voltage

τ = Beam current on-time

Since 1 calorie is equal to 4.186 joules and since 1 joule equals 1 watt-second, then

$$T_{max} \times M \times C = (300)\ (0.05)\ (0.2)\ (4.186)$$

$$= 12.5 \text{ watt-sec/cm}^2$$

From the preceding calculations, it is estimated that the maximum possible power that can be applied to the phosphor at any time in one pulse cannot exceed 12.5 watt-seconds/cm^2.

4.2.1 CRT Writing Speed Analysis. To determine some of the fundamental limitations in the writing speed of the EPIC System, a theoretical analysis was performed. In addition, it was necessary to correlate the theoretical analysis with the measurement results obtained with the General Dynamics Electronics and Litton cathode-ray tubes.

In the following analyses, some of the operation parameters described were derived from experimentation and some from current literature. In all cases, the general correspondence of theoretical and practical calculations was considered verification of the formulas expressed. An examination of the data presented will permit a determination of which parameters may be improved to achieve a faster writing system.

The first parameter to be calculated is concerned with the efficiency of conversion of electrical energy to radiant ultraviolet energy in the phosphor, as described by the formula

$$\text{Radiant Energy} = NVI_D\ \tau\ \eta_P$$

where η_P = efficiency of the P16 phosphor in converting electrical energy to UV radiant energy (typical 4 per cent)

The spectrum of the radiant energy described in the preceding formula peaks around 3800 angstroms and the absorption curve for a typical photochromic dye peaks at about 3600 angstroms. The two curves are shown in Figure 2. The absorption curve of the photochromics is typical, and may vary depending on the type of dye. Also, the curve shown for the P16 phosphor is typical. With the two typical curves shown, the efficiency of absorption of ultraviolet energy by the photochromic material is approximately 58 per cent.

$$\eta\lambda = 0.58$$

where $\eta\lambda$ = efficiency of energy transfer from the P16 phosphor to the photochromic material

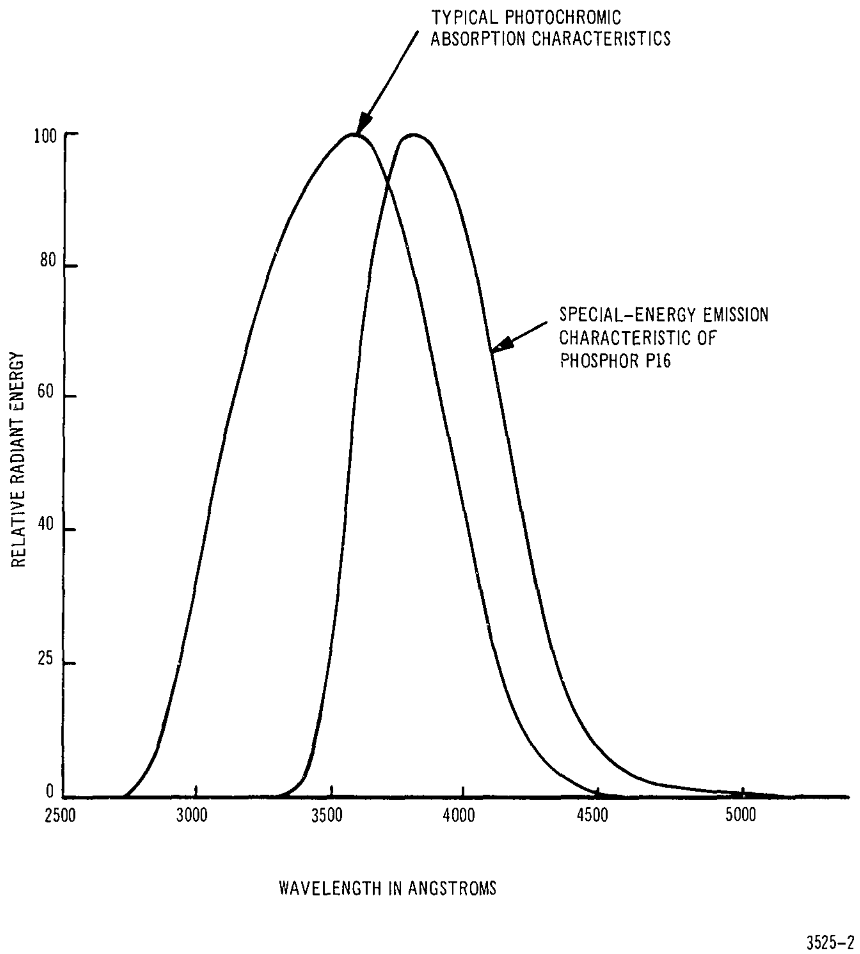

Figure 2. Comparison of P16 Emission and PC Absorption

The next factor to be considered is the transmission efficiency of the fiber-optic face plate. Figure 3 shows a typical transmission curve of efficiency of fiber optics for two fiber-optic thicknesses. This is superimposed with the P16 spectral transmission. From this curve, it is seen that the fiber-optic efficiency (η_F) is approximately 0.9.

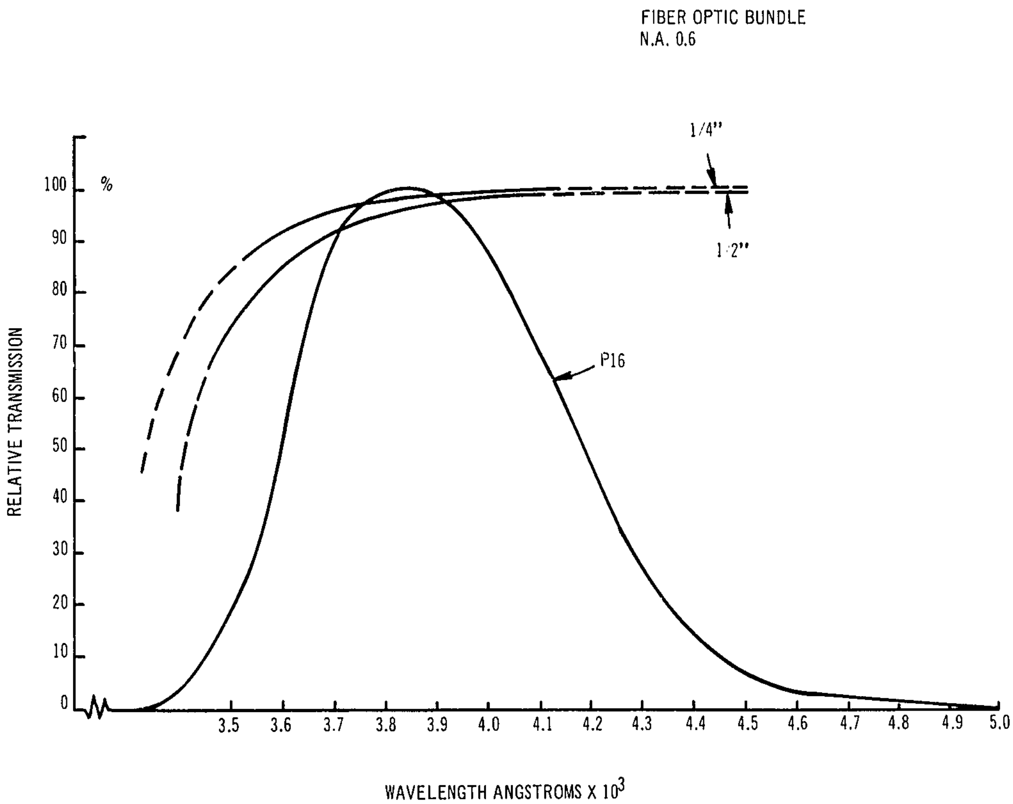

Figure 3. Typical Fiber Optic Transmission for a Collimated Beam Perpendicular Incidence

A curve of density versus log of exposure for photochromic material is shown in Figure 4. Combining the factors discussed in the preceding paragraphs, the energy reaching the photochromic material is

$$\text{Energy} = N\ V\ I_D\ \eta_P \times \tau\ \eta_\lambda\ \eta_F$$

where Energy = watt-seconds per square centimeter

For any energy calculated by the preceding formula, the optical density to which the photochromics is written can be determined from the curve of Figure 4.

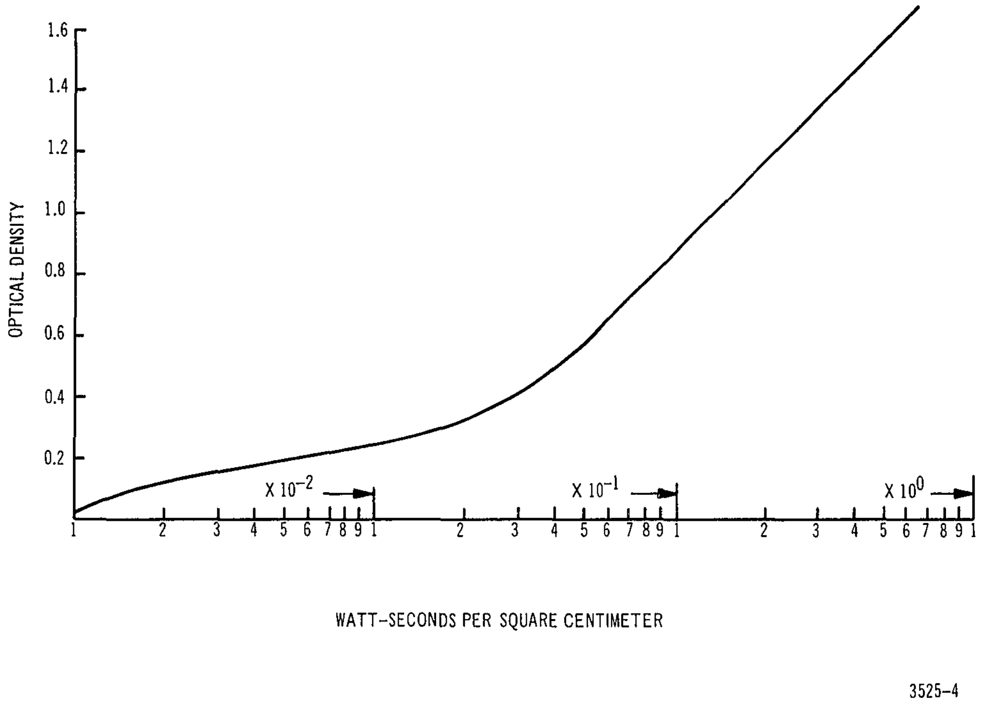

Figure 4. Photochromic Writing Density versus Exposure

4.2.2 Verification of Analysis Using GDE Tube. The following analysis is made to verify the analysis of the preceding paragraph and to compare with experimental data. The data in Table 4 was obtained as a result of measurements with the GDE Charactron Tube used to expose photochromics.

TABLE 4. GDE CHARACTRON TUBE CHARACTERISTICS

CHARACTERISTIC	SPECIFICATION
Ultor Voltage	24 kv
I	10 microamperes
τ	500 microseconds
N	125 pulses required to reach an optical density of approximately one
Character Height	0.05 inch

Assuming a square character, the character area is

$$\text{Area A} = \left(0.05'' \times \frac{2.54\ \text{cm}}{\text{in.}}\right)^2$$

$$= 1.62 \times 10^{-2}\ \text{cm}^2$$

$$\text{Area A} = \text{Area}$$

In the preceding equation, the area of the character lines is assumed to be 10 per cent of the total character area or 1.62×10^{-3} cm.

The current density is

$$I_D = \frac{I}{A}$$

$$= \frac{10 \times 10^{-6}}{1.62 \times 10^{-3}}$$

$$= 6.17 \times 10^{-3}\ \frac{\text{amp}}{\text{cm}^2}$$

then the total energy reaching the P16 phosphor is

$$\text{Energy}_{P16} = I_D\ V \tau N$$

$$= (6.17 \times 10^{-3})\ (24 \times 10^{3})\ (500 \times 10^{-6})\ (125)$$

$$= 9.25\ \text{watt-sec/cm}^2$$

Utilizing the previously defined constants

$$\eta_P = 4\ \text{per cent}$$

$$\eta_\lambda = 0.58$$

$$\eta_F = 0.9$$

The energy reaching the photochromics is given by

$$\text{Energy}_{PC} = \text{Energy}_{PC}\ \eta_P\ \eta_\lambda\ \eta_F$$

$$= (9.25)\ (0.04)\ (0.58)\ (0.9)$$

$$= 0.192\ \text{watt secs/cm}^2$$

From the curve of Figure 4, this energy should write to an optical density of approximately 1.25 on the photochromic material which corresponds closely to the initally assumed optical density.

In addition to a determination of the integrated light output capability of the phosphor, it is necessary to ascertain the phosphor heating characteristics to prevent burning or permanent damage to the phosphor. Past experience indicates that permanent damage will not occur in typical phosphors, if the average power density does not exceed 10-15 watt second per cm^2.

A parameter of the GDE tube which has not been thoroughly analyzed is the heat transfer method in the phosphor-CRT glass combination. Further study in this area should provide information on heat limitations and method of increasing the power density capability.

To ascertain the phosphor heating characteristics, the energy per unit area per pulse is an important factor. The energy per unit area/pulse is given by

$$\frac{\text{Energy}}{\text{Area}} = V \tau I_D$$

$$= (2.4 \times 10^4)(500 \times 10^{-6})(6.17 \times 10^{-3})$$

$$= 0.074 \text{ watt-secs/cm}^2$$

4.2.3 Verification of Analysis Using Litton CRT. The same analysis is to be applied to the data obtained with the measurements on the Litton fiber-optic CRT. Results with the Litton device indicate that writing to a full optical density on Kalvar film requires 250 milliseconds. Since the Kalvar film sensitivity is known to be approximately 0.1 watt-seconds per square centimeter, the validity of the above formula can be checked in this manner.

The characteristics of the Litton CRT are listed in Table 5. This is the same tube as listed in Table 2, but with different parameters.

TABLE 5. LITTON CRT CHARACTERISTICS

CHARACTERISTIC	SPECIFICATION
Tube Type	E2A16B
Ultor Voltage	40 kv
Beam Current	10 microamperes
Spot Size	2 mils
1 inch line scan time	67 microseconds
Flyback time	10 microseconds
Total scan time	77 microseconds
Area of 2-mil spot	2.5×10^{-5} cm^2

The total scan time is 77 microseconds, and since 250 milliseconds is required to write Kalvar to the proper optical density, the total number of sweeps required is

$$\frac{250 \times 10^{-3}}{77 \times 10^{-6}} = 3.24 \times 10^{3} \text{ sweeps}$$

assuming a 500-line resolution system, the pulse width is

$$\frac{67 \times 10^{-6}}{500} = 1.33 \times 10^{-7} \text{ seconds}$$

The total energy per unit area reaching the Kalvar film is

$$\frac{\text{Energy}}{\text{Area}} = I_D \; V \; \tau \; N \; \eta_P \; \eta_F$$

$$= \frac{10 \times 10^{-6}}{2.5 \times 10^{-5}} (40 \times 10^{3}) (1.33 \times 10^{-7}) (3.24 \times 10^{3}) (0.58) (0.04) (0.9)$$

$$= 0.144 \text{ watt-sec/cm}^2$$

Since the sensitivity of Kalvar film is approximately 0.1 watt-sec/cm^2, the calculation also helps verify the above formula and measurements.

To determine if the phosphor is heated excessively, it is necessary to calculate the energy per area

$$\frac{\text{Energy}}{\text{Area}} = V I_D \tau$$

$$= 40 \times 10^3 \left(\frac{10 \times 10^{-6}}{2.5 \times 10^{-5}}\right) (1.33 \times 10^{-7})$$

$$= 2.12 \text{ milliwatt-sec/cm}^2$$

Since this figure is quite low, no phosphor damage should result.

4.2.4 Phosphor Investigations at NCR Dayton. To investigate other techniques of increasing the phosphor light output, a trip was made to the Dayton facility of NCR. Dr. Maclin Hall of the Physical Research Department recently completed a study program on the applicability of the solution spray process in the preparation of phosphor screens. The conventional phosphor coating technique is a settled powder type of process. The solution spray process provides a film type of phosphor coating. Although the primary purpose of this study was to provide increased resolution capability, some of the work is directly applicable to providing increased light output. One of the advantages of the phosphor film technique is that the phosphor film is more resistant to electron burn which as noted previously is one of the main limitations of the conventional phosphor CRT screens. In addition, the film provides a phosphor of greater packing density which should in turn, provide greater heat conductivity and in addition, greater light-output. The implications of this technique should be explored further.

4.2.5 Projection Considerations. One of the fundamental questions which must be answered before proceeding with the detailed equipment design is the type of projection to be used. Two fundamental types of projection are possible: reflective and transmissive.

A typical transmissive type of projection system is shown in Figure 5. In this system, the projection source is used to illuminate the rear of the phosphor. This provides the projection illumination for the photochromic data. In this type of a system, a transparent or partially transparent phosphor must be used.

A typical reflective type of projection is shown in Figure 6. In this type of system, an external illuminating light source is directed at and reflected from the front surface of a cathode-ray tube.

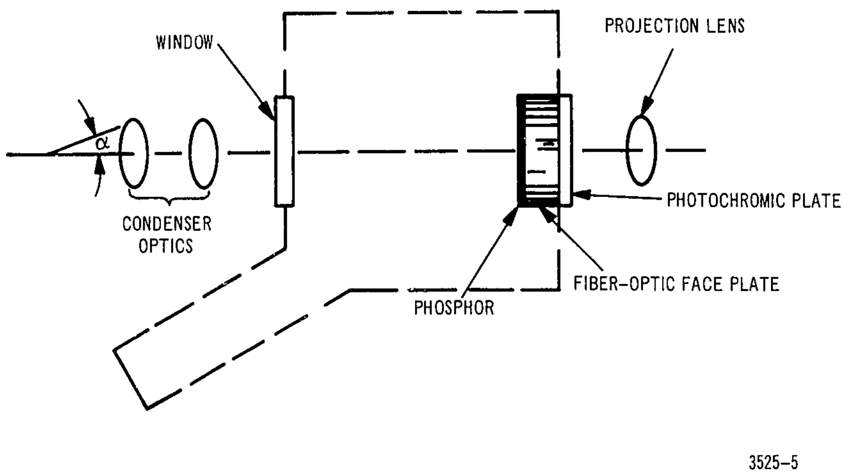

Figure 5. Transmissive Projection Technique

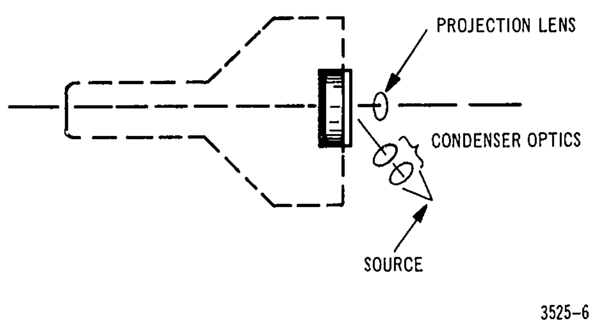

Figure 6. Diffusing Reflective Projection Technique

To properly evaluate the various types of projection systems, a number of factors must be considered:

a. Efficiency of projection system.

b. Can a conventional CRT envelope be used?

c. Cost and complexity of the optical system.

d. Ability to superimpose one or more additional image planes.

e. Reliability and maintainability.

In the following paragraphs, the luminous efficiency of a number of optical systems that can be utilized in a CRT Display System are evaluated. Following, a typical calculation is made for the transmissive projection system. The efficiency of the reflective and Schmidt optical systems, are calculated in a similar fashion. Wherever necessary, additional comments are made with regard to parameters that are not covered in the typical calculation. The symbols to be used in this section are contained in Table 6.

TABLE 6. SYMBOL DEFINITIONS

SYMBOLS	EXPLANATION
S	Source
C	Condenser Optics
PC	Photochromics
Ph	Phosphor
FO	Fiber Optics Face Plate
P	Projection Lens
M	Mirror
M_P	Primary Mirror
S_C	Schmidt Corrector
- - - -	Extent of CRT Envelope
α	Half angle subtended by the condenser input pupil with respect to a point source

TABLE 6. (CONT)

SYMBOLS	EXPLANATION
θ	Half angle subtended by the projection lens input pupil with respect to the intersection of the lenses' optical axis with the fiber-optic face plate
K_C	Per cent transfer of condenser lens; this factor includes losses due to reflections and absorption and the positioning effects of the source with regard to the lens
K_L	Per cent transmission of projection lens; this factor includes losses due to reflections and absorption and the positioning effect of the source with regard to the lens
L_C	Per cent losses due to reflection and absorption for a condenser lens
L_P	Per cent losses due to reflection and absorption for a projection lens
L_E	Luminous Efficiency $= \frac{\text{lumens emitted by projection lens}}{\text{lumens emitted by source}} \times 100$

4.2.5.1 Typical Calculation of Transmissive Projection.

The lumens transferred by the Condenser C (see Figure 5) to the phosphor are a function of:

a. The number of steradians subtended by the condenser input pupil with respect to the point source S.

b. The losses due to the absorption of the condenser optics.

c. Losses due to reflections at the surfaces of the condenser elements.

The per cent of the total flux K_C emitted by the point source that is intercepted by the input pupil of the lens and is transferred to the phosphor is

$$K_C = \left[\frac{1 - \text{Cos}\ \alpha}{2}\right] L_C$$

Where L_C = the lens constant (a factor determined by losses due to absorption and reflection)

For the purpose of this report, the case considered will be that of an f/1, two element condenser which introduces losses of 20 per cent per element for the respective factors of reflection and absorption. Therefore

$$\alpha = 2.6^{\circ}$$

$$L_C = (1 - 0.2)(1 - 0.2) = 0.64$$

$$\text{and } K_C = 100 \times \left[\frac{1 - \cos\alpha}{2}\right] L_C$$

$$= 100 \times \left[\frac{1 - 0.89}{2}\right] (0.64)$$

$$= 3.5\%$$

Seventy per cent of the light flux incident upon a chemically deposited P16 phosphor will be reflected, while 30 per cent will be transmitted into the fiber optics face plate. Ten per cent of the flux transmitted through the face plate will be absorbed. The projections lens will transfer approximately

$$K_p = L_p \operatorname{Sin}^2\theta \times 100$$

where L_p = Lens constant (assumed to be 0.85)

$\theta = 14^{\circ}$ (for an f/2 lens)

$\therefore K_p = (0.85)(0.242)^2 \times 100$ (when magnification is equal to or greater than 10)

$= 5\%$

Table 7 summarizes the flux that each component transfers from the component preceding it to the component following it.

TABLE 7. TRANSMISSIVE PROJECTION

COMPONENT	PERCENTAGE TRANSFER
C	3.5
Ph	30
FO	90
PC	90
L	5

As a result of all the factors described, the luminous efficiency of the system will be

$$L_E = (0.035)\ (0.3)\ (0.9)\ (0.9)\ (0.05)\ (100)$$

$$= 0.043\%$$

The following optical systems are calculable in a similar fashion. Previous assumptions regarding K_C and K_P are utilized wherever applicable in the following systems.

4.2.5.2 Calculation of Reflective Projection Efficiency.

With regard to Figure 6, the per cent transfer of luminous energy via the fiber optics-phosphor-photochromic combination occurs as follows.

a. 70 per cent is transmitted through the air-photochromic substrate interface.

b. It is assumed that the photochromics and fiber optics are each about 95 per cent efficient.

c. 70 per cent is reflected by the phosphor.

d. 96 per cent is transmitted through the glass-air interface.

e. The 30 per cent mentioned in item a is reflected by a mirror M (reflection factor = 80 per cent) back onto the face plate where a, b, c, and d occur again.

To calculate the total energy loss in a number of components, it is necessary to use the product of the losses of each component. The condenser system has been estimated to be 3.59 per cent efficient and the projection lens 5 per cent. The remainder of the energy loss occurs in the PC-Fiber Optics Phosphor components. The efficiency of the system in transmitting energy through these components is given by

$$\text{Eff (PC-FO-Ph)} = (0.7)\ (0.95)\ (0.95)\ (0.7)\ (0.95)\ (0.95)\ (0.96)$$

Para.	a	b	b	c	b	b	d
		PC	F.O.	F.O.	PC		

$$= 0.38 \text{ (or 38\%)}$$

An additional amount of energy of the 30 per cent reflected from the first component (PC glass) is captured by the mirror M. Of this amount it is assumed that about 80 per cent is reflected by the mirror. The light energy returned by the mirror is:

$$(0.38)\ (0.3)\ (0.8) = 0.09 \text{ (or 9\%)}$$

The total light leaving these multiple interfaces is then the sum of the two listed above, or

$$E_{ff}\ (PC - FO - Ph) = 0.38 + 0.90$$

$$= 0.47$$

The efficiencies of energy transfer are summarized in Table 8.

TABLE 8. REFLECTIVE PROJECTION

COMPONENT	PERCENTAGE TRANSFER
C	3.5%
PC-FO-Ph	47%
L	5%

The overall luminous efficiency L_E is equal to the product of the individual efficiencies, or

$$L_E = (0.035)\ (0.47)\ (0.05) = 8.23 \times 10^{-3}$$

$$L_E = 0.08\%$$

A parabolic or elliptical collector will increase the per cent transfer of C by a factor of approximately 15. All luminous efficiency figures should be increased by a factor of approximately 15 if this type of collector is considered for systems 1 and 2.

4.2.5.3 Calculation of Schmidt Optical Efficiency

A Schmidt Optical System is illustrated in Figure 7. This method of illumination requires the use of an elliptical reflector condenser. The calculations are very similar to the previous example. In Figure 7 it is assumed that the large mirror C collects about 60 per cent of the available light energy. The remainder of the components are similar to the previous example. It was also estimated that the Schmidt corrector was transmitting 90 per cent of the incident energy. Table 9 contains a summary of the individual component efficiencies.

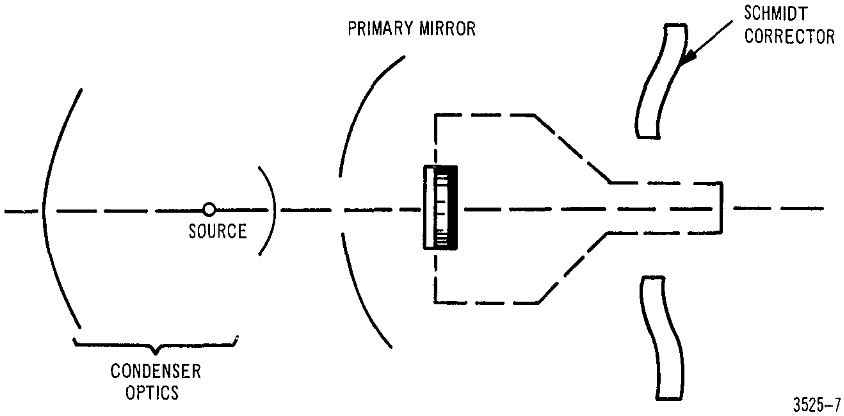

Figure 7. Modified Schmidt Optical System

TABLE 9. SCHMIDT OPTICAL COMPONENT TRANSFER

COMPONENT	TRANSFER
C	60%
PC-FO-Ph	38%
M_P	34%
S_C	90%

The luminous efficiency is then given as the product of the individual efficiencies, or

$$L_E = (0.6)\ (0.38)\ (0.34)\ (0.9) = 0.0698$$

$$L_E = 6.98\%$$

4.2.5.4 Screen Brightness.

Screen brightness for a white matte screen can be determined by:

$$B_S = \frac{L_E (T) \operatorname{Cos}^4 \theta}{S_A}$$

where B_S = screen brightness expressed in foot lamberts

L_E = luminous efficiency of optical system

T = total lumen output of source expressed in lumens

S_A = screen area expressed in square feet

θ = angle between optical axis of projection lens and the elemental area of the screen consideration.

4.2.5.5 Aluminized Phosphor.

Another fundamental consideration is to determine whether or not the phosphor should be aluminized. First, since aluminizing makes the CRT screen opaque, it would essentially eliminate a transmissive type of projection system. A number of advantages accrue from the use of an aluminized coating:

a. Output of the ultraviolet phosphor may be increased by a factor of two, since the aluminum is a good reflector, thereby providing a possible increase in writing speed.

b. No charge accumulation occurs because of the electrical conduction characteristics of the aluminum.

c. Aluminized coating provides a physical barrier against phosphor poisoning, i.e., the phosphor is protected from poisoning by oil or other foreign materials remaining in the evacuated tube. Consequently the phosphor life is increased.

d. It has been expressed that the aluminum backing may be useful as a heat sink, thereby increasing the thermal capacity of the phosphor. This effect must be investigated.

It is concluded that the advantages of the aluminized phosphor are important enought to eliminate the systems shown in Figures 5 and 6. Also, the optical efficiency of a reflective system is an advantage. Therefore, preference will be given to further study of the capabilities of the system illustrated in Figure 6. A summary of the comparisons among the three systems is presented in Table 10.

TABLE 10. COMPARATIVE MERITS OF OPTICAL SYSTEMS

SYSTEM	LUMINOUS EFFICIENCY	COMMENTS
Transmissive	0.043%	Needs a special CRT
Reflective	0.08%	Does not need a special CRT
Schmidt	6.98%	Requires Schmidt optics

4.2.6 Special Projection System. The optics for a typical reflective CRT projection system was illustrated in Figure 6. In examining some of the factors affecting the projection efficiency, it is noted that considerable improvements can be obtained by increasing the reflection efficiency of the CRT fiber optic interface. One possible method of accomplishing this is shown in Figure 8. A detailed drawing of components contained in the CRT face is shown in Figure 9.

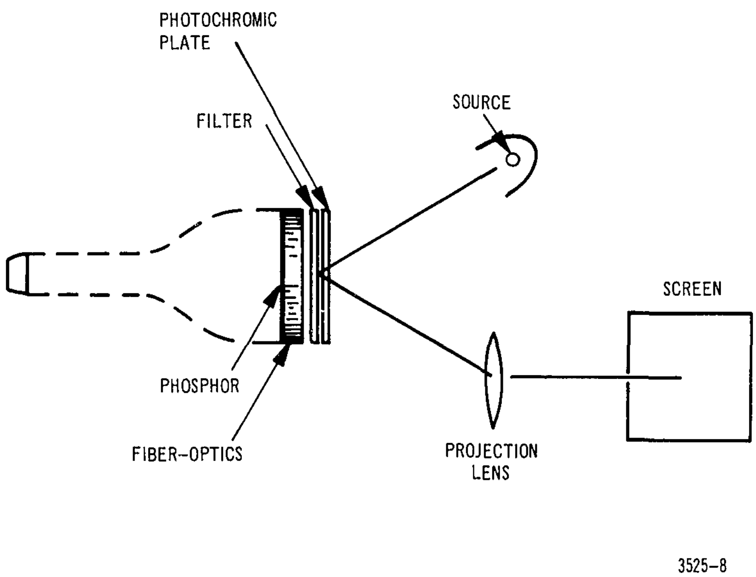

Figure 8. Specular Reflective CRT Projection System

The dichroic filter characteristics are such that ultraviolet impinging within a 60 degree cone onto the surface is transmitted efficiently. Visible light at an off-axis angle is reflected from this surface. The use of this technique offers a number of advantages. First, the projection efficiency of the system is improved considerably. Secondly, blemishes or imperfections in the fiber optics or phosphor are not illuminated by the projection light and therefore are not projected onto the screen.

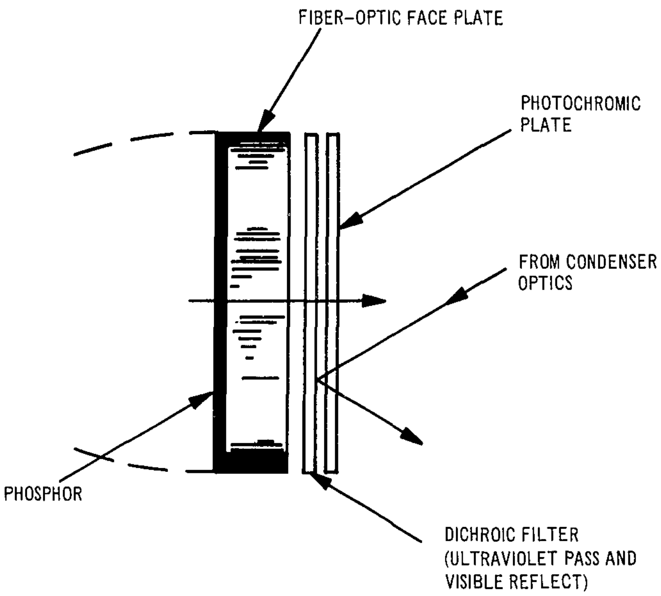

Figure 9. Detail of CRT Face Plate

Another advantage is the projection light does not reach the phosphor. Otherwise, the heat of the projection light would decrease the efficiency of the phosphor.

Manufacturers of dichroic mirrors have been contacted on the feasibility of making this type of dichroic. At least one manufacturer has stated that the technique is feasible. A sample dichroic will be procurred and evaluated as soon as more data is obtained.

4.2.7 CRT Selection Criteria. Another very important consideration in system design is the electrical characteristics of the CRT. One of the first selections to be made is concerned with the type of deflection and focus to be used. CRT's are generally categorized according to the following characteristics.

a. Electrostatic focus and deflection.

b. Electrostatic focus and deflection, using post acceleration.

c. Electrostatic focus and magnetic deflection.

d. Magnetic focus and deflection.

e. Electrostatic focus, and electrostatic incremental deflection, and magnetic main deflection.

f. Magnetic focus, electrostatic incremental deflection, and magnetic main deflection.

Generally, electrostatic deflection and focus tubes have a deflection factor of from 85 to 200 volts per inch which eliminates the use of simple transistor circuitry. In addition, the spot diameters are generally large: typically, 30 mils at 5 kv for a 5VP1 tube. The CRT display requires about a 2-mil spot. In addition, the spot growth at the edges of the face plate is also objectionable. Edge defocussing is another common problem.

One method of increasing the deflection sensitivity is to utilize post acceleration. With this technique, the deflection factor can be reduced to about 25 to 30 volts per inch; however, spot growth and focus are still problems. This essentially eliminates the first two categories.

The magnetic deflection, electrostatic focus tubes offer the advantages of simple focus hardware, i.e., a higher practical accelerating potential limit with a smaller spot and with very little edge defocussing. The deflection amplifiers generally used for this type of system are larger and slower; however, light output of a magnetically deflected CRT is much higher.

When magnetic focus is used instead of electrostatic focus, a very small spot diameter results as well as an increase in hardware size and complexity. This type of tube offers the highest resolution.

The last two types use small electrostatic deflection plates (dither plates) for high-speed writing. That is, the magnetic deflection is used as a coarse type of deflection to center the character and the electrostatic plates are then driven to trace out the character. Deflection factors are generally in the 100 to 200 volts per inch region. Edge distortion and defocussing is prevalent in these tubes as it is with straight electrostatic deflection system..

It is generally accepted that since the photochromic material sensitivity is relatively low, it will be necessary to utilize multiple sweeps to expose characters or lines. Since magnetic deflection provides a higher light output, and since they are the most readily available tubes for our purpose, it is anticipated that the breadboard will be constructed using magnetically deflected CRT. The type of focus to be used will either be magnetic or electrostatic depending on the availability of a suitable CRT.

Since there are many unknowns about the system operation, the first breadboard constructed will have to be quite versatile, having the capability of working with different high voltages, beam currents, stroke rates for characters, etc. Therefore, it is required that the magnetic deflection amplifier have the highest possible speed obtainable at a reasonable cost. The following general parameters were established for procurement of a magnetic deflection amplifier.

a. Capable of positioning and writing characters with the same yoke in a random manner

b. Solid state

c. Minimum cost

d. Operating in a laboratory environment

The properties of a magnetic deflection amplifier-yoke system are basically described by the following equations.

$$I_D = K_D \sqrt{V_A}$$

where I_D = deflection current in amperes

V_A = accelerating voltage

K_D = proportionality constant

$$I_D = \frac{K_L}{L_Y}$$

where L_Y = effective yoke length

K_L = proportionality constant

$$L = K_Y N^2$$

where L = yoke inductance

N = number of turns

K_Y = proportionality constant

$$i_D = \frac{V}{R}\left(i - e^{\frac{-Rt}{L}}\right) \qquad \text{(eq. 1)}$$

where i_D = instantaneous yoke current

V = effective charging voltage

R = effective total series resistance

L = yoke inductance

t = time to reach the specified current

$$\alpha \approx K_\alpha I_D N$$

where K_α = proportionality constant

α = total deflection angle

N = number of yoke turns

A Celco Pacific Deflection Amplifier Model DAPP-6 was chosen as the best commercially available unit which meets the requirements. A trip was made to the Celco Pacific plant at Upland, California to observe a working deflection amplifier breadboard. The properties of this device are as listed in Table 11.

TABLE 11. DEFLECTION AMPLIFIER CHARACTERISTICS

CHARACTERISTIC	SPECIFICATION
Power Supplies	±20 volts at 12A ea
Max. current per channel	±6 A
Input impedance	10K
Sensitivity	±1 volt per ±2A
Effective series resistance	0.5 ohm
Effective charging voltage	15V
Load Range	10 to 100 μh

A 25-microhenry yoke was used as load. The observed rise time for a 12-ampere swing was 24 microseconds. The manufacturer quotes that the amplifier response to a step function as described by

$$t = \frac{LI}{E}$$

where L = yoke inductance

E = 15 volts

I = desired current

This neglects any effective series resistance. Equation 1 solved for time gives

$$t = -\frac{L}{R} \ln \left(1 - \frac{i_D R}{V}\right) \qquad \text{(eq. 2)}$$

Figure 10 shows a comparison of current rise times using both these equations.

Figure 11 shows the minimum yoke inductance for full deflection of a 42-degree CRT utilizing the full output of the Celco DAPP-6 amplifier. It may be seen that a 25-microhenry yoke will drive any 42-degree CRT with accelerating potentials to 30 kv.

Figure 12 shows current for full deflection at various accelerating potentials with a 25-microhenry yoke and the minimum full screen deflection time for a step input to the amplifier. The time is calculated using the pessimistic eq. 2. These values are all calculated and must be confirmed with the actual hardware.

The stroke rate for stroke written characters presented through this amplifier is determined by character height, font, and human factor considerations. A theoretical stroke rate maximum will be determined.

5. CONCLUSIONS

a. Preliminary design of the CROW System has been accomplished and feasibility established. Further verification of the operation of this system must be obtained by laboratory evaluation.

b. Extensive theoretical analysis of CRT writing on photochromics has been completed, checked with experimental data, and verified.

c. The projection to be used with the CRT will be a reflective type using conventional optics.

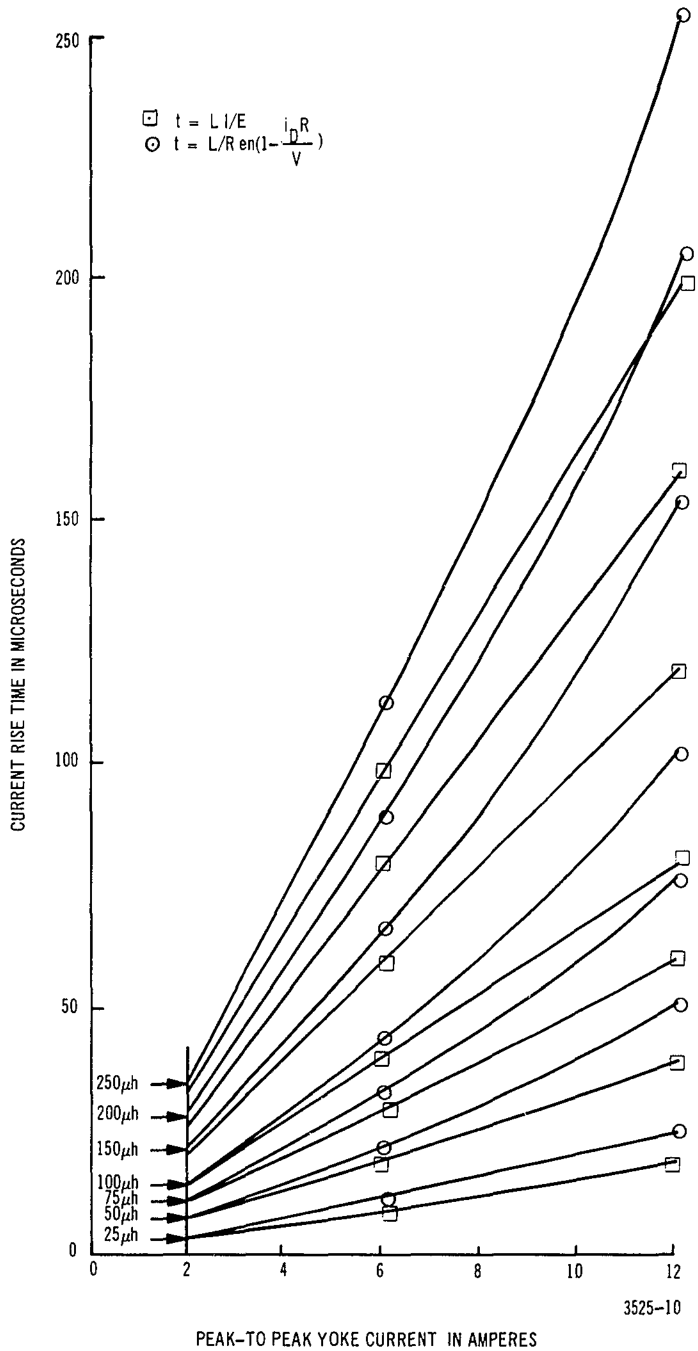

Figure 10. Current Rise Times

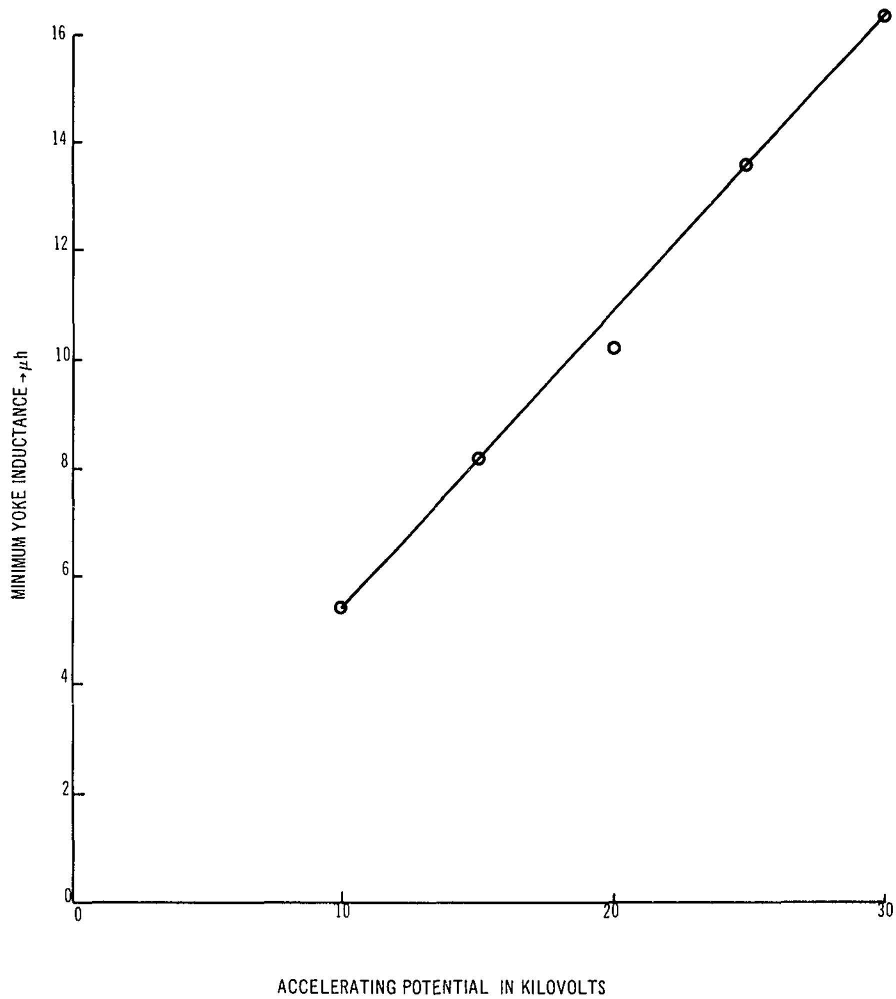

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Figure 11. Minimum Yoke Inductance

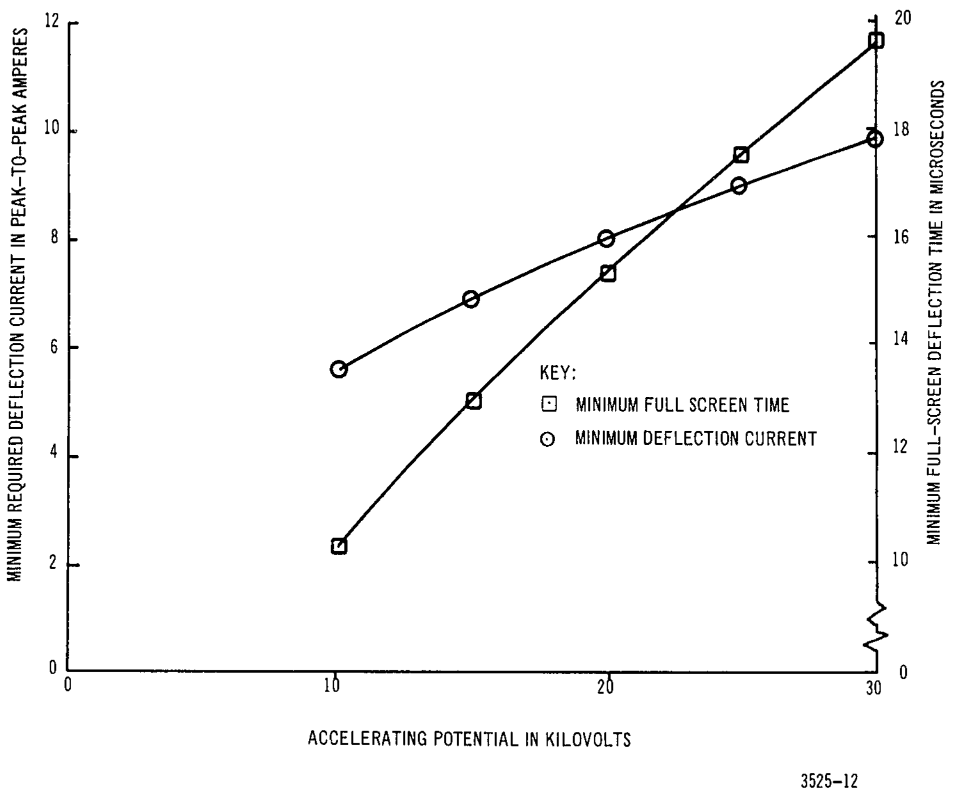

Figure 12. Full Deflection at Varying Accelerating Potential

d. Further investigation of the CROW display technique will be de-emphasized at this time in favor of concentrating on the Electronics PhotochromIC (EPIC) system. This conclusion is based on the greater potential offered by the latter system and the practical limitations of funds and time.

e. Sufficient preliminary design has been accomplished to proceed with fabrication of the breadboard for the Electronic PhotochromIC CRT system.

6. PROGRAM FOR NEXT QUARTER

a. Complete system design on EPIC System.

b. Order and fabricate components for EPIC System.

c. Initiate assembly and evaluation of EPIC System.

7. IDENTIFICATION OF PERSONNEL

Key personnel working on this project are Messrs. H. Bjelland, Project Engineer; S. Mak and W. Leisner. Resumes of these personnel were included in the First Quarterly Report. The resume of Mr. W.A. Stein who has recently started working on this project is included below.

WILLIAM A. STEIN

Senior Design Development Engineer at NCR Electronics Division. B.S. in Engineering from UCLA; EIT Certificate. NCR: CRT and associated electronic components research and development. Marquardt Corporation: CRT display systems, drum storage and computer display interface, high-speed character generation. Aerojet General Corporation: Automatic firing sequencers, magnetic components, animated missile trainers.

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UNCLASSIFIED

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During the second period of this contract, effort has been directed toward completing theoretical evaluation of the Counter-rotating Optical Wedge (CROW) system and continuation of the design of the Electronic PhotochromIC CRT (EPIC) system. Analyses are included on the phosphor, projection, and system considerations of this display technique. Efficiency calculations were made for different EPIC systems.

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